 EL970860893US

APPARATUS AND METHODS OF CONTROLLING SURFACE CHARGE AND FOCUS

Inventors:

Mark A. McCord; Jan Lauber; Paul Petric; Ross Thompson; Jason Lim; Frank Fan; and Gabor D. Toth

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of provisional patent application no. 60/503,640, filed September 17, 2003, entitled "Apparatus and Methods of Controlling Surface Charge and Focus", by inventors Mark A. McCord, Jan Lauber, Paul Petric, Ross Thompson, Jason Lim, Frank Fan, and Gabor D. Toth, the disclosure of which is herby incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to specimen inspection and review. More particularly, the present invention relates to electron beam inspection and review systems.

Description of the Background Art

Automated inspection and review systems are important in process control and yield management for the semiconductor and related microelectronics industries. Such systems include optical and electron beam (e-beam) based systems.

In the manufacture of semiconductor devices, detection of electrical failure earlier in the fabrication process is becoming increasingly important to shorten product development cycles and increase product yield and productivity.

Advanced wafer inspection systems based on scanning electron microscopy technology has been used to detect electrical failure in-line as voltage contrast defects. However, as device design rules further shrink, and new processes (such as, for example, high aspect ratio (HAR) contacts in front-end-of-line (FEOL), HAR vias in back-end-of-line (BEOL), and dual damascene copper processes) are being widely implemented, it becomes more challenging to detect voltage contrast defects in ever increasing high aspect ratio device structures. Further, image contrast variation caused by uneven charge distribution can make e-beam inspection unstable or un-inspectable. Such contrast variation can occur from inside a die, from die to die, row to row, or wafer to wafer. In order to successfully inspect a wafer, control of surface charge is advantageous to 1) detect voltage contrast defects effectively, and 2) reduce image contrast variation during inspection.

FIG. 1 is a simplified diagrammatic representation of a conventional scanning electron microscopy configuration **100**. As shown, a beam of electrons **102** is scanned over a sample **104** (e.g., a semiconductor wafer). Multiple raster scans **112** are typically performed over a small area **114** of the sample **104**. The beam of electrons **102** either interact with the sample and cause an emission of secondary electrons **106** or bounce off the sample as backscattered electrons **106**. The secondary electrons and/or backscattered electrons **106** are then detected by a detector **108** that is coupled with a computer system **110**. The computer system **110** generates an image that is stored and/or displayed on the computer system **110**.

Typically a certain amount of charge is required to provide a satisfactory image. This quantity of charge helps bring out the contrast features of the sample **104**. Although conventional electron microscopy systems and techniques typically produce images having an adequate level of quality under some conditions, they produce poor quality images of the sample for some applications. For example, on a sample **104** made of a substantially insulative

material (e.g., silicon dioxide), performing one or more scans over a small area causes the sample to accumulate excess positive or negative charge in the small area relative to the rest of the sample **104**. The excess charge generates a potential barrier for some of the secondary electrons, and this potential barrier inhibits some of the secondary electrons from reaching the detector **108.** Since this excess positive charge is likely to cause a significantly smaller amount of secondary electrons to reach the detector **108**, an image of the small area is likely to appear dark, thus obscuring image features within that small area. Alternatively, excess negative charge build up on the sample can increase the collection of secondary electrons causing the image to saturate. In some cases, a small amount of charging is desirable since it can enhance certain image features (by way of voltage contrast) as long as it does not cause image saturation.

The excess charge remaining from a previous viewing or processing may therefore cause distortion. One solution used in SEM devices is to flood the sample with charged particles from a separate flood gun at a time separate from the inspection. This flooding equalizes the charge appearing across the sample **104**, thus improving the voltage contrast images. One drawback to this flooding procedure is the need to move the stage including the entire sample to the area of the flood gun. In order to accomplish the flooding, the inspection must stop to permit movement of the sample **104** to the area of the flood gun. This dramatically increases the overall time required for the inspection since movement and flooding of the sample may take ten minutes or more to complete. This produces an equally dramatic decrease in the throughput for the inspection process. Typically a full inspection of a sample **104** will require hundreds of scan lines across the sample and the dissipation of charge may be required after only a few scan lines have been completed. The total time required for a sample **104** to be inspected therefore is the sum of the separate intervals for charge dissipation (or precharging) and inspection.

In regards to the focus of an electron image, a change in the surface charge for the area being imaged can also cause the image to go out of focus. In addition, a change in the height of the area being imaged may cause the image to go out of focus. Existing techniques to deal with these variations in surface charge and sample height include measuring surface charge with a Kelvin probe or secondary electron cut-off points and measuring the sample height by way of light or capacitative sensors. The data from these measurements may then be used to determine an adjustment of the focus. However, these existing techniques are disadvantageously complicated and/or inefficient. For example, measurement of surface charge with a Kelvin probe involves a large area to make the measurement and is typically slow.

Hence, as discussed above, efficient and effective control over the charge on the surface of a sample **104** is desirable to improve the speed of obtaining images and the quality of images obtained during electron beam inspection or review. Furthermore, it is desirable to improve techniques for focusing an electron image in dependence on surface charge and sample height variations.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified diagrammatic representation of a conventional scanning electron microscopy configuration.

FIG. 2 is a schematic diagram of an electron beam inspection system in accordance with an embodiment of the invention.

FIG. 3 is a diagram depicting stage bias control circuitry in accordance with an embodiment of the invention.

FIG. 4 is a graph of test results showing resultant surface charge levels as a function of stage bias levels in accordance with an embodiment of the invention.

FIG. 5 is a flow chart depicting a first method for setting a surface charge level of an area of a specimen in accordance with an embodiment of the invention.

FIG. 6 is a flow chart depicting a second method for setting a surface charge level of an area of a specimen in accordance with an embodiment of the invention.

FIG. 7 is a schematic diagram depicting focusing of an incident electron beam onto a specimen surface.

FIG. 8 is a schematic diagram depicting focusing of an incident electron beam onto a specimen surface using an apparatus in accordance with an embodiment of the present invention.

FIG. 9 is an illustrative diagram depicting a two-dimensional in-focus band in accordance with an embodiment of the present invention.

FIG. 10 is a graph depicting a one-dimensional in-focus band in accordance with an embodiment of the present invention.

SUMMARY

One embodiment of the invention pertains to a method of setting a surface charge of an area on a substrate to a desired level. The substrate is held on a stage, and a stage bias voltage applied to the stage is controlled. A flood of electrons is directed to the area. The stage bias voltage is controlled such that the surface charge of the area reaches an equilibrium at the desired level.

Another embodiment of the invention pertains to a method of auto-focusing a main electron beam incident upon an imaging area of a substrate. A monitor electron beam is generated and directed towards a monitoring area of the substrate at a non-perpendicular incidence angle. An in-focus band in data

collected from the monitor beam is detected. The focal length of an objective lens focusing the main beam is adjusted based upon a position of the in-focus band.

DETAILED DESCRIPTION

FIG. 2 is a schematic diagram of an electron beam inspection system **200** in accordance with an embodiment of the invention. The e-beam system **200** generates and directs an incident electron beam **201** towards an area of interest on a sample **206**. As shown in FIG. 2, the electron beam **201** may be generated by an electron gun **202**. A column **204** including various components in a vacuum is used to direct the electron beam **201** towards the surface of the sample **206**. The column **204** typically includes various electron lenses, apertures, and other components.

In accordance with an embodiment of the invention, the sample **206** is on a biased stage **208**. The biased stage **208** is coupled to control circuitry that is configured to control and set the voltage bias level of the stage **208**. One embodiment of the control circuitry is described below in relation to FIG. 3. Like the column **204**, because the incident beam comprises electrons, a vacuum system **210** is used to pump the chamber containing the sample or specimen **206** and biased stage **208** (as well as the column **204**). The sample may comprise, for example, a wafer or other substrate. A wafer transport system **212** may be used to move wafer samples to be inspected in-line as part of a manufacturing process.

In accordance with an embodiment of the invention, one or more electron flood guns **214** are included in the e-beam system **200**. The flood gun(s) **214** may be utilized to flood the wafer with a broad beam of electrons prior to inspection being performed. In addition, or alternatively, a Wehnelt electrode (not

shown) may also be included above the sample. The voltage on the Wehnelt electrode may be varied to control the surface charge on the wafer.

The e-beam system **200** also includes a detector (not shown) configured to detect charged particles (secondary electrons and/or backscattered electrons) emitted from the sample. The e-beam system **200** may also include an image generator (not shown) for forming an image from the detected emitted particles.

FIG. 3 is a diagram depicting stage bias control circuitry in accordance with an embodiment of the invention. The control circuitry includes a microcontroller **304** that sets the stage bias voltage using a digital-to-analog converter (DAC) **306** and reads back the stage bias voltage, beam current, and charge voltage via an analog-to-digital converter (ADC) **316**. A serial interface **302** may be used for communications between the system controller (not shown) and the microcontroller **304**. Using the serial interface **302**, the system controller can set the stage bias level.

The output of the DAC **306** is amplified to an appropriate voltage by an amplifier **308** and fed into one input of an isolation amplifier **310**. This drives the other input of the isolation amplifier **310** to the desired voltage level. This other input is connected to the stage **208** and sample (for example, wafer) **206**.

The bias voltage output by the amplifier **308** is also attenuated by an attenuator **318** and may be fed into the ADC **316** as the stage bias readback signal. This allows the stage bias voltage to be monitored by the controller **304**.

Beam currents to the wafer **206** may also be monitored by reading the output of the isolation amplifier **310**. The output of the isolation amplifier **310** is a voltage that is a measure of the total beam current. This voltage may be fed into the ADC **316** as the beam current readback signal. This allows a measure of the beam current to be sampled by the microcontroller.

In addition, a charge sensor **312** is configured within proximity to the surface of the specimen (for example, wafer) **206**. The charge sensor **312**

measures the charge deposited on the specimen. The output of the sensor **312** may be fed into the ADC **316** as the charge readback signal. This voltage may also be monitored by the controller **304**.

FIG. 4 is a graph of test results showing resultant surface charge levels as a function of stage bias levels in accordance with an embodiment of the invention. The horizontal axis is a stage bias voltage level that is set prior to flooding. The vertical axis is a voltage that gives a measure of surface charge on the sample after flooding. As seen, the surface charge is an almost linear function of stage bias. As depicted, the more positive the stage bias voltage, the more negative the surface charge. The more negative the stage bias voltage, the more positive the surface charge. Hence, it is shown that the surface charge can be controlled by setting the stage bias and then flooding with electrons.

FIG. 5 is a flow chart depicting a first method **500** for setting a surface charge level of an area of a specimen in accordance with an embodiment of the invention. This method **500** involved adjusting the stage bias to achieve the desired surface charge.

The area on the specimen is selected **502** for surface charge control. A stage bias is set **504** at a voltage level. Flooding **506** is performed on the area by an electron flood beam. The flooding **506** is preferably performed sufficiently long such that the surface charge reaches an equilibrium level. The equilibrium surface charge depends on the stage bias in a manner similar to the test data illustrated in FIG. 4. The exact dependence will depend on the nature of the specimen and may vary from system to system. The resultant surface charge level is read **508** using a sensor or probe. A determination **510** is made as to whether the surface charge is at the desired level or whether adjustment is needed. If adjustment of the surface charge is needed, then the bias level may be changed **512**, and the process **500** loops back to setting **504** the stage bias to the changed level, flooding **506** the area, and so on. If no adjustment is needed, then the process **500** of setting the surface charge level ends.

Following this process **500**, for example, e-beam inspection or review of the area may be performed. The inspection or review may include the use of voltage contrast. Advantageously, by controlling the surface charge level, the effect of voltage contrast can be greatly enhanced, manifesting voltage contrast defects that may not appear otherwise. The number of voltage contrast defects detected may thus be considerably increased, providing a more true representation of defectivity issues, such as defect distribution and defect density data on the wafer. Such data is essential for fabrication defect and process engineers to correct process problems and improve manufacturing yield. Further, contrast variation may also be advantageously reduced, enabling more successful inspections.

FIG. 6 is a flow chart depicting a second method **600** for setting a surface charge level of an area of a specimen in accordance with an embodiment of the invention. This method **600** makes a series of measurements over a range of stage biases to determine the dependency of surface charge on stage bias. Knowing the dependency, the desired surface charge may be achieved by setting the stage bias accordingly.

The area on the specimen is selected **602** for surface charge control. A stage bias is set **604** at an initial voltage level. Flooding **606** is performed on the area by an electron flood beam. The flooding **606** is preferably performed sufficiently long such that the surface charge reaches an equilibrium level. The resultant surface charge level is read **608** using a sensor or probe.

A determination **610** is made as to whether the desired range of voltages for the stage bias has been covered or completed. If the range has not been completed, then the stage bias is incremented **612**, and the process **600** loops back to flooding **606** the area, reading **608** the surface charge, and so on. If the range has been completed, then the process **600** moves on to use **614** the data obtained to set the stage bias so as to achieve the desired surface charge. In other words, once the dependency of surface charge on stage bias has been

determined, the dependency function may be used to set the stage bias so as to achieve the desired surface charge.

Following this process **600**, for example, e-beam inspection or review of the area may be performed. The inspection or review may include the use of voltage contrast. Advantageously, by controlling the surface charge level, the effect of voltage contrast can be greatly enhanced, manifesting voltage contrast defects that may not appear otherwise.

The above-described techniques control surface charge of a semiconductor wafer or other specimen through flooding. During flooding, the stage is biased to control the final charge on the specimen surface. The stage can be biased either negatively or positively, depending on the desired final charge on the wafer surface.

The above-described techniques include both “manual” and “automatic” modes. In manual mode, an area on the specimen to be flooded is first selected. A stage bias is selected, and flooding is performed. Then, the charge after flooding is read with a charge measurement device. In automatic mode, a test process is used to perform flooding at different stage biases over a prescribed range, and a curve or function is generated from the test. An example of such test results is shown in FIG. 4. The curve or function is then used to select the stage bias, and flooding is performed to achieve the desired surface charge.

Detection of electrical failure as voltage contrast defects is important in yield management in semiconductor manufacturing. The above-described techniques for controlling surface charge levels can substantially enhance the performance of e-beam inspection systems in the detection of voltage contrast defects. The above-described techniques may also enable or improve the performance of inspection on wafers that may otherwise charge severely during the inspection. The above-described techniques may be implemented, for example, on a scanning electron microscope based inspection

or review tool. They may also be implemented on a direct imaging (non-scanning) electron microscope based system, or an energy-dispersive x-ray system, or other systems.

FIG. 7 is a schematic diagram depicting focusing of an incident electron beam onto a specimen surface. An objective lens **702** of an electron column focuses the "main" incident beam **701** on the specimen surface **704**.

Two factors affect the focus and result in out-of-focus conditions. One factor is the lens-to-surface distance **706**. In other words, variation in the mechanical height of the specimen surface can cause a resultant electron image to be out of focus. Variation in mechanical height is typically measured with light or capacitative sensors. A second factor is the level of charge on the specimen surface **704**. This is typically measured with a Kelvin probe or using secondary electron cut-off points. Neither measuring the first factor nor measuring the second factor alone provides adequate information to determine the required focal length for the electron imaging tool during a review or inspection run. Hence, prior techniques make two separate measurements to determine both mechanical height and surface charge.

FIG. 8 is a schematic diagram depicting focusing of an incident electron beam onto a specimen surface using an apparatus in accordance with an embodiment of the present invention. In addition to the components shown in FIG. 7, a monitor beam gun **802** is included in the configuration of the apparatus. The monitor beam gun **802** may comprise, for example, an electron beam generating by a relatively low-cost flood gun with scanning capabilities. The monitor beam **804** may be imaged with relatively low-resolution (for example, around 0.1 to 1 micron resolution).

The monitor beam **804** is incident upon the specimen surface **704** at a non-perpendicular angle. In a preferred embodiment, the monitor beam **804** is incident upon the surface **704** at a relatively low angle (alpha) from around 10 to 30 degrees (as measured from the plane of the surface). Preferably, the field-

of-view (FOV) for the monitor beam **804** is such that FOV multiplied by cosine (alpha) is many times larger than the depth-of-field (DOF) of the monitor beam. For example, in accordance with a preferred embodiment, FOV multiplied by cosine(alpha) may be one hundred times or more than the DOF.

In one embodiment, the monitor beam **804** may be configured to periodically scan a single frame with a fixed focal length. Conventional lower electron detectors may be used to capture the signal for the image. During the scan of the monitor beam **804**, the high-resolution imaging beam (the "main" beam) **701** is preferably turned off or blocked out. This is to avoid undesirable interference between the two beams. After scan of the monitor beam **804** is completed, the high-resolution imaging beam **701** may be turned on or unblocked.

Due to the tilted incidence angle and the DOF being much smaller than the FOV, an image acquired by the monitor beam **804** will contain a distinct in-focus band, surrounded by out-of-focus regions. At best focus conditions, the in-focus band will be positioned at a certain location in the FOV. Keeping fixed the focal length of the monitor beam **804**, a subsequent shift up or down of the in-focus band then indicates a change in <u>either</u> the specimen height or surface charge. As such, the position of the in-focus band is correlated with and indicative of the focus conditions of the main imaging beam at that area. In other words, this technique provides a single measurement of the combined focus metric contributions from both wafer height variation and surface charge variation. This single measurement is advantageous over the dual measurements required by the conventional techniques. The overhead time to maintain focus of the main beam **701** can be substantially reduced using this technique in comparison to conventional techniques. The overhead time of this technique comprises the time it takes to acquire the monitor image, compute the position of the in-focus band, and set the main beam focal length accordingly. Preferably,

the overhead time takes a few hundred milliseconds or less. This is substantially faster than conventional auto-focus routines.

In addition to the monitoring purpose, the monitor beam gun **802** may also serve the purpose of pre-charging the wafer at the imaging area per the techniques described above. Hence, in one embodiment, the monitor gun **802** may comprise one of the flood guns **214** depicted in FIG. 2. In another embodiment, the monitor gun **802** may comprise a separate electron gun.

FIG. 9 is an illustrative diagram depicting a two-dimensional in-focus band in accordance with an embodiment of the present invention. The diagram illustrates a two-dimensional image **902** captured by the monitor beam. Due to the tilt of the monitor beam, the image has an in-focus band **904** surrounded by out-of-focus areas **906**.

In an actual implementation, the field of view may be of a different shape than that illustrated. Furthermore, the in-focus band **904** preferably comprises a smaller fraction of the field of view than the fraction illustrated.

In accordance with one embodiment, the monitor beam is directed to a same area as is being imaged by the main beam. In accordance with another embodiment, the monitor beam is directed to a separate area that is relatively near the area being imaged by the main beam, such that the focal metric derived from the monitor beam is still a meaningful focal metric for the main beam. In the latter embodiment, the monitor beam and the main beam may both be on at the same time.

Preferably, the area imaged by the monitor beam has sufficient detail to enable an algorithm to accurately locate the in-focus band **904**. The algorithm to locate the in-focus band **904** may comprise, for example, determining the band in the image **902** with the most high-frequency spatial content (or edge content). That determination may be accomplished, in part, by taking a Fourier transform of the captured image **902**. The band with the most high-frequency spatial content should correspond to the in-focus band **904**, while

areas with less high-frequency content should typically correspond to the out-of-focus areas **906**.

FIG. 10 is a graph depicting a one-dimensional in-focus band in accordance with an embodiment of the present invention. The x-axis of the graph represents the location **1002** along one dimension of the image from the monitor beam. The one dimension would correspond to the vertical dimension of the image shown in FIG. 9. The y-axis of the graph represents the edge content **1004** for the band at that location along the one dimension. The edge content is a measure of the high-frequency spatial content in the band.

As depicted in FIG. 10, the edge content **1004** is highest in a "band" around a location along the one dimension. That location corresponds to the location of the in-focus band **1006**.

As described above, tracking a location of an in-focus band in an image from a tilted monitor beam may be used to measure a focal metric applicable to the main imaging beam. Advantageously, the focal metric so derived from this single measurement accounts for variations in both structural height and surface charge.

A different technique involves a separate measurement of wafer height and surface charge. If real-time closed loop height sensing hardware is included to compensate for wafer height variation, the surface charge measurement remains as the only task. Measurement of surface charge with a Kelvin probe is typically slow and involves too large of an area. Instead, the following surface charge measurement may be advantageously used for auto-focusing.

An electron detector equipped with a proper energy filter may be used for measuring the secondary electron cut-off point. The electron detector with energy filter may comprise, for example, a detector located in an upper region of the column. Such a detector may be ramped through a voltage range (from +100 volts to -100 volts, for example) with respect to the wafer bias. During

this fast voltage ramp, signal is acquired but an image is not formed. The acquired signal as a function of energy filter voltage will exhibit a distinct bright-to-dark (high-to-low) transition. The position and width of this transition is determined by and indicative of the surface charge. The main beam imaging system will then set the objective lens focal length accordingly and start the image capture with the correct focal length. Since this is a single voltage ramp on the energy filter, the charge measurement process is advantageously expected to take less than 100 milliseconds.

The above-described diagrams are not necessarily to scale and are intended be illustrative and not limiting to a particular implementation. The above-described invention may be used in an automatic inspection or review system and applied to the inspection or review of wafers, optical masks, X-ray masks, electron-beam-proximity masks and stencil masks and similar substrates in a production environment.

In the above description, numerous specific details are given to provide a thorough understanding of embodiments of the invention. However, the above description of illustrated embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise forms disclosed. One skilled in the relevant art will recognize that the invention can be practiced without one or more of the specific details, or with other methods, components, etc. In other instances, well-known structures or operations are not shown or described in detail to avoid obscuring aspects of the invention. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize.

These modifications can be made to the invention in light of the above detailed description. The terms used in the following claims should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims. Rather, the scope of the invention is to be

determined by the following claims, which are to be construed in accordance with established doctrines of claim interpretation.